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Procedures required to provide precise ephimerides for Geodetic Positioning System (GPS) satellites are described, ~~herein~~. The ephimerides predicted will be used as source data for the determination of one's precise position in three dimensions to 10 m accuracy anywhere in the world. Signals from these satellites will also be used to determine the trajectory of fleet ballistic missiles.

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FOREWORD

In the mid 1980's, the NAVSTAR Geodetic Positioning System (GPS) will include 27 satellites in orbits having periods of 12 hours. Using signals from these satellites, a user may compute his position in three dimensions instantaneously to 10 m accuracy anywhere in the world. A demonstration of this system will be possible several hours each day in 1978 making use of observations of four out of six satellites which will be in orbit at that time. During the development period, the Naval Surface Weapons Center, Dahlgren Laboratory (NSWC/DL), will compute predicted positions of the satellites each week. As a result of these computations, NSWC/DL will have source data in convenient form for the determination of precise positions of the satellite after-the-fact, as opposed to the predicted ephemeris which will be broadcast by the satellite.

The Applied Physics Laboratory of Johns Hopkins University (APL/JHU) will use signals from the GPS satellites transponded by fleet ballistic missiles during development tests to determine the trajectory of the missiles. To assist APL/JHU in this SATRACK program the Navy Strategic Systems Office requested NSWC/DL to provide precise ephemerides for the GPS satellites and related data. This report describes the procedures adopted to meet this requirement.

The CELEST computer program used to determine satellite orbits was designed by Dr. James W. O'Toole and modifications for GPS applications were developed by Dr. Michael D. Harkins. The program used to combine CELEST output for various satellites to obtain a simultaneous solution was designed and tested by Patrick J. Fell. Extensions of the program to meet SATRACK requirements were made by J. Edwin Johnson; NSWC/DL SATRACK Program management during FY 1976 was under Paul H. Taylor and during FY 1977 was under Phillip L. Young. This report was reviewed and approved by R. J. Anderle, Head, Astronautics and Geodesy Division.

Released by:

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Warfare Analysis Department

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INTRODUCTION

PRINCIPLE OF THE NAVSTAR GEODETIC POSITIONING SYSTEM

Navigation using the NAVSTAR Geodetic Positing System (GPS) is based on the principle that a user can determine his position if he can measure the range to three satellites at known positions. Each satellite will generate a pseudo random noise (PRN) signal at precisely designated times; if the user can determine the time of receipt of this signal, the user can compute the range to the satellite by multiplying the difference between time of transmission and time of receipt of the signal by the velocity of light. However, both the satellite clocks and the user clock would have to be accurate to about 5 ns for this procedure to produce an accuracy of 10 m in user position. The satellite clocks will be maintained to this accuracy by daily calibration. However, the user will have to measure the time difference to a fourth satellite, and, with the four time differences, solve for the error in the user clock as well as the three components of this position.

EPHEMERIS COMPUTATIONS FOR THE GPS

Each satellite will broadcast its position in real time from values which are injected into its memory each day by the same Master Control Station (MCS) which calibrates its clock. The MCS will predict the satellite position and clock behavior using a sequential filter. To minimize the computer workload at the MCS, reference trajectories and partial derivatives for the sequential filter will be provided by the Naval Surface Weapons Center, Dahlgren Laboratory (NSWC/DL), about once a week (during the development phase of the GPS). These reference trajectories need only be accurate to 0.1 to 1.0 km to be within the linear range of the sequential filter. Although the MCS must predict both the position of each satellite and the clock corrections for each satellite for injection in the satellite memory, NSWC/DL need only predict the position of each satellite for use by the MCS as a reference.

PRINCIPLE OF GPS EPHEMERIS COMPUTATIONS AT NSWC/DL

Simulations have shown that adequate precision can be obtained in computed satellite orbits if the observations are treated as range differences. For example, Figure 1 shows the standard error in computed satellite positions for the following conditions:

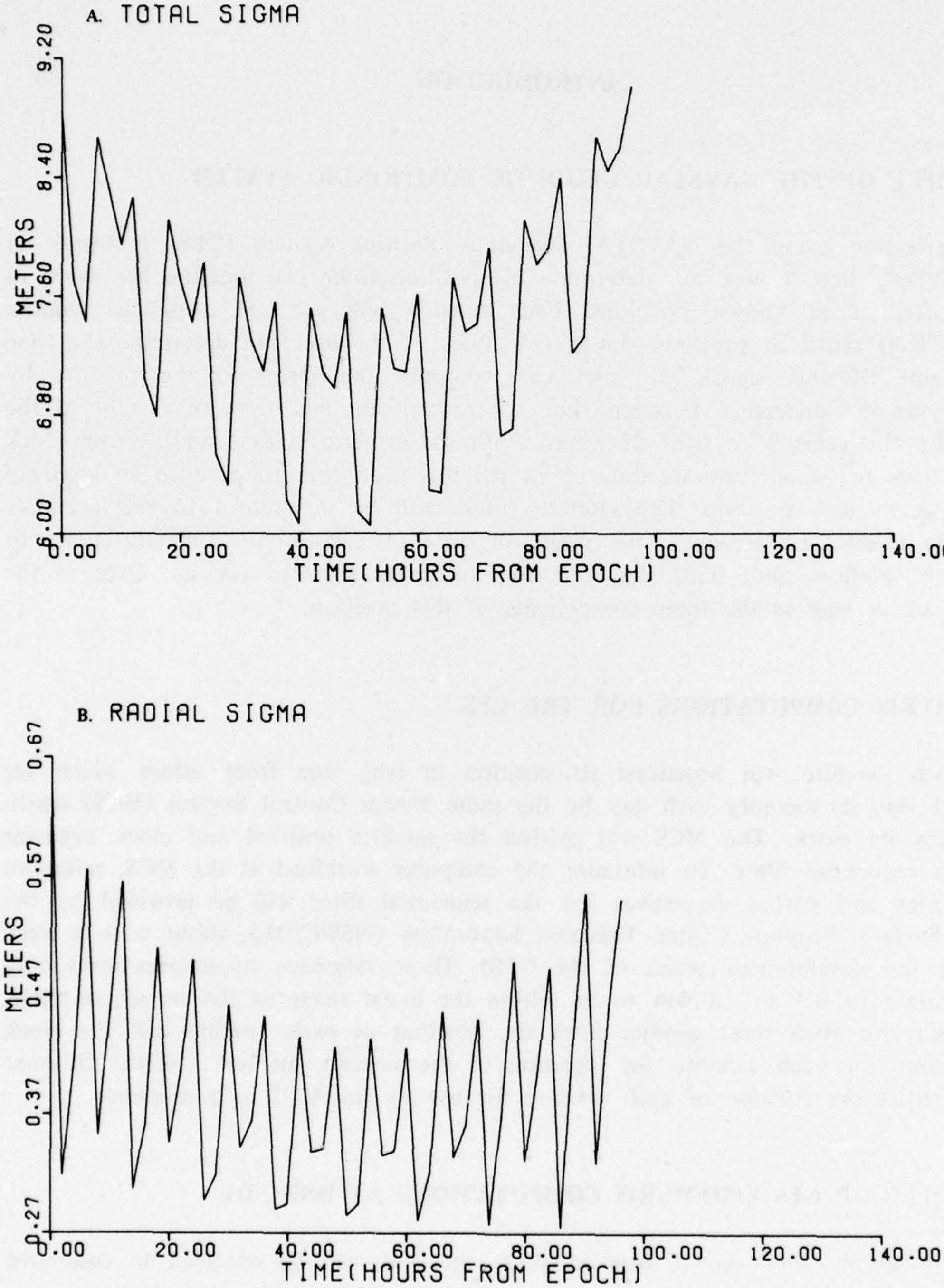


Figure 1. Standard Error in Satellite Data Position Computed from Range Difference Data

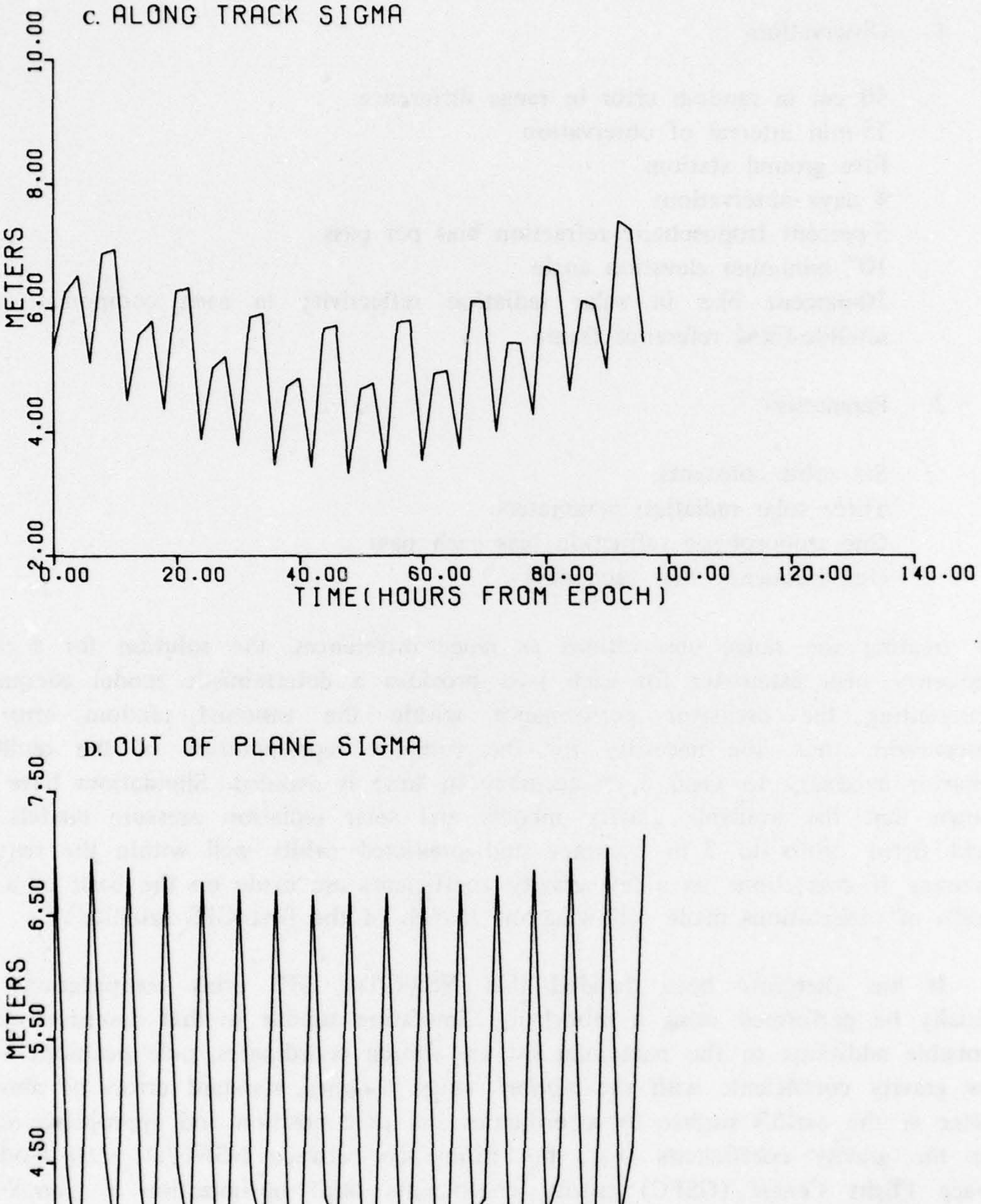


Figure 1. Standard Error in Satellite Data Position Computed from Range Difference Data (Continued)

1. Observations

50 cm in random error in range difference
15-min interval of observation
Five ground stations
4 days observations
5-percent tropospheric refraction bias per pass
10° minimum elevation angle
10-percent bias in solar radiation reflectivity in each component in a satellite-fixed reference frame

2. Parameters

Six orbit constants
Three solar radiation parameters
One tropospheric refraction bias each pass
One frequency bias each pass

By treating the range observations as range differences, the solution for a single frequency bias parameter for each pass provides a deterministic model adequately representing the oscillator performance within the assumed random error of observation; thus, the necessity for the complex representation of the oscillator behavior necessary to yield 5 ns accuracy in time is avoided. Simulations have also shown that the available gravity models and solar radiation pressure models will yield fitted orbits to 2 m accuracy and predicted orbits well within the required accuracy if corrections to a few gravity coefficients are made on the basis of a few weeks of observations made following the launch of the first GPS satellite.[1,2]

It has therefore been decided that NSWC/DL GPS orbit computations will initially be performed using a model for simulation similar to that described above. Probable additions to the parameter list are station coordinates, pole position, and a few gravity coefficients with the ***a-priori*** values assigned standard errors of about a meter at the earth's surface for coordinates and pole position and appropriate values for the gravity coefficients (e.g., the difference between NSWC/DL and Goddard Space Flight Center (GSFC) gravity coefficients until optimization is completed). However, NSWC/DL also has a responsibility to provide definitive orbits to the GPS Joint Project Office for purposes of analysis. Under this task, it is desirable to utilize the greater strength of the range observations and to employ a better model of the errors in the oscillator and the forces on the satellite. Therefore, a sequential processor is being developed at a lower priority which will be capable of representing these errors as process noise in a computer program which will retain some of the analysis flexibility which now exists in the current batch processor.

PRINCIPLE OF EPHEMERIS COMPUTATIONS FOR SATRACK APPLICATIONS

SATRACK requires a precise orbit as well as precise satellite clock representation but does not require these data in real time. The MCS ephemeris is not suitable for this purpose because it is optimized for prediction while the NSWC/DL orbit is not suitable because it does not include clock corrections. However, a program had been developed at NSWC/DL which would operate from the outputs of the CELEST computer program for single satellites to obtain a combined satellite solution for satellite positions and clock corrections.[3] It was believed that with suitable modifications, this program would produce orbits to 2 m accuracy and clock corrections to 5 ns accuracy for the SATRACK applications with low risk. The required modifications were:

1. Special output formats required for compatibility with APL/JHU computer programs

2. Extension of the CELEST single satellite covariance propagation to apply to the multiple satellite results

3. Combination of range and range difference data

While better accuracy and statistical integrity would be achieved with the use of process noise, it is felt that such an approach would carry a higher risk because of the time required to develop the computer program. Particularly, time is required to optimize the parameters so that improved accuracy is achieved during periods of observation without degradation of accuracy during unobserved periods.

The third program modification is critical to the success of the interim use of the batch processor for the SATRACK application. It is believed that several days of observation are required to achieve the desired orbit accuracy. However, since the simple oscillator model is not adequate over such a time period, the data must be treated as range differences, and a frequency bias parameter must be determined for each satellite pass. In order to obtain the clock corrections required for SATRACK application, range observations will be included for several hours near the launch time. By simultaneous solution for orbit and clock parameters using both range and range difference data it is expected that the accuracy objective will be met and that the standard errors of the parameters will be reasonable. Figure 2 shows standard errors for the conditions given in the previous example, except for the addition of range data for a 4-hour period at 15-min intervals with a 0.5-m random error and quadratic clock model for the satellite and the five stations with the standard errors for the ***a-priori*** data given in Table 1.

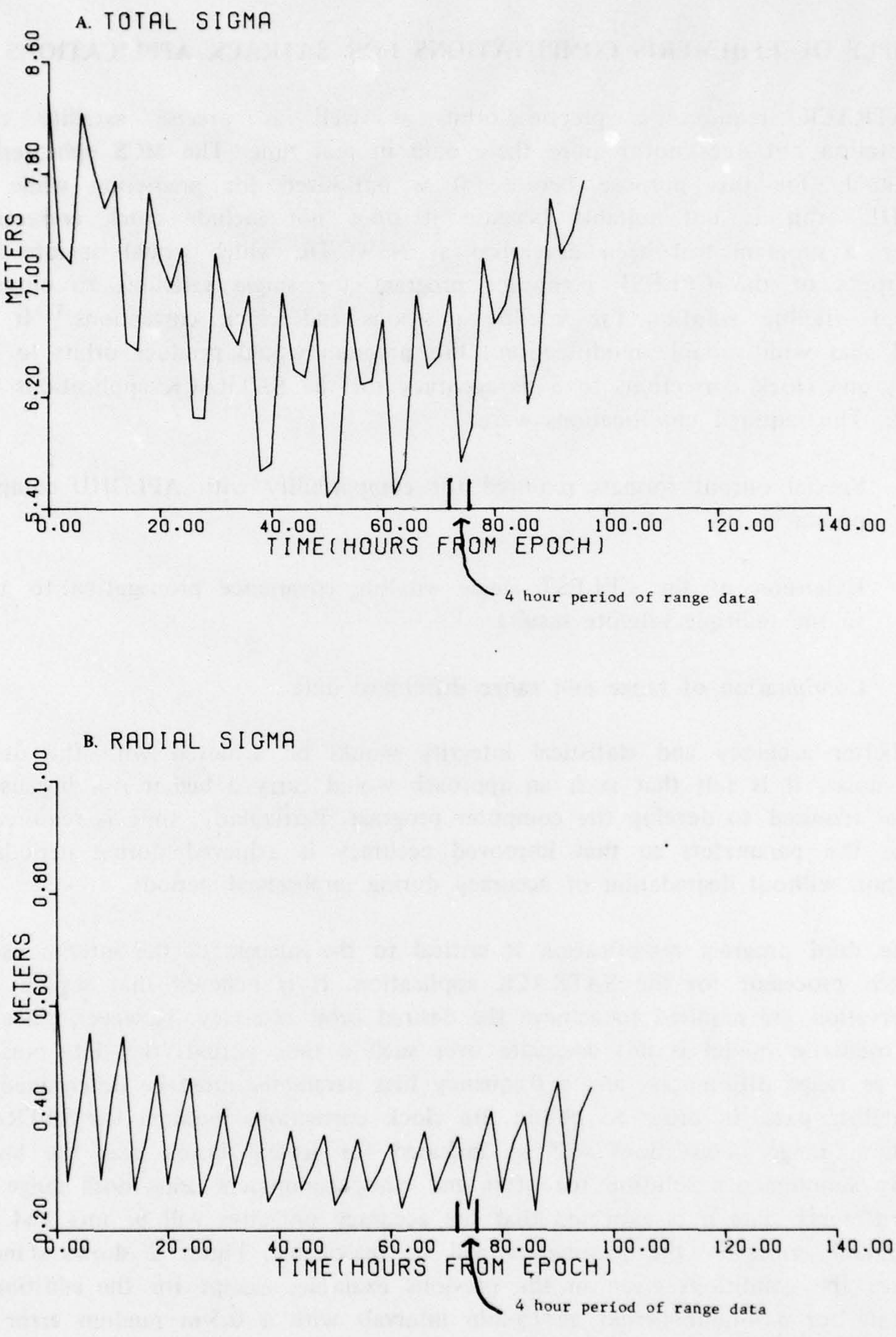
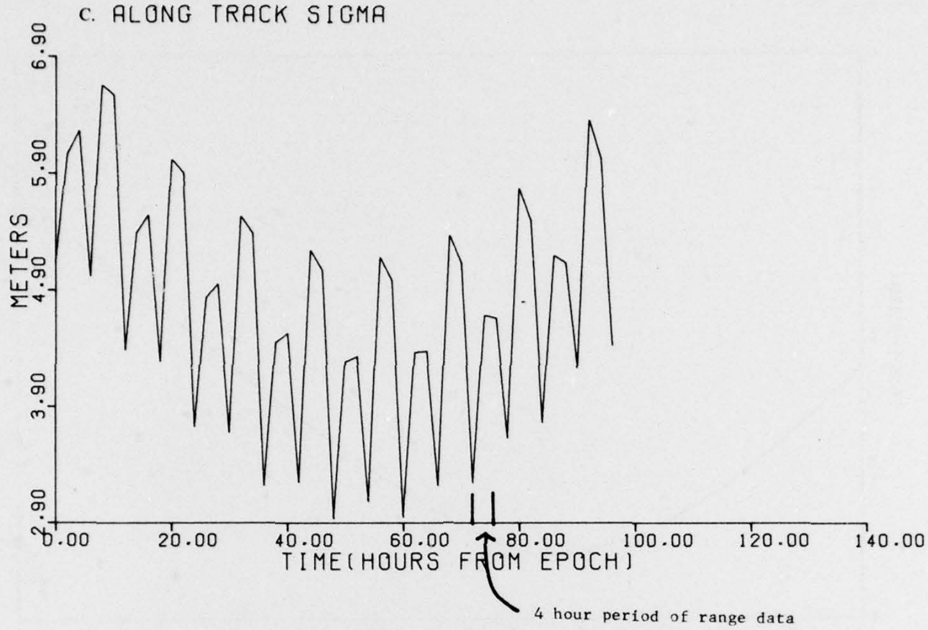


Figure 2. Standard Error in Satellite Position and Clock Bias from Range and Range Difference Data



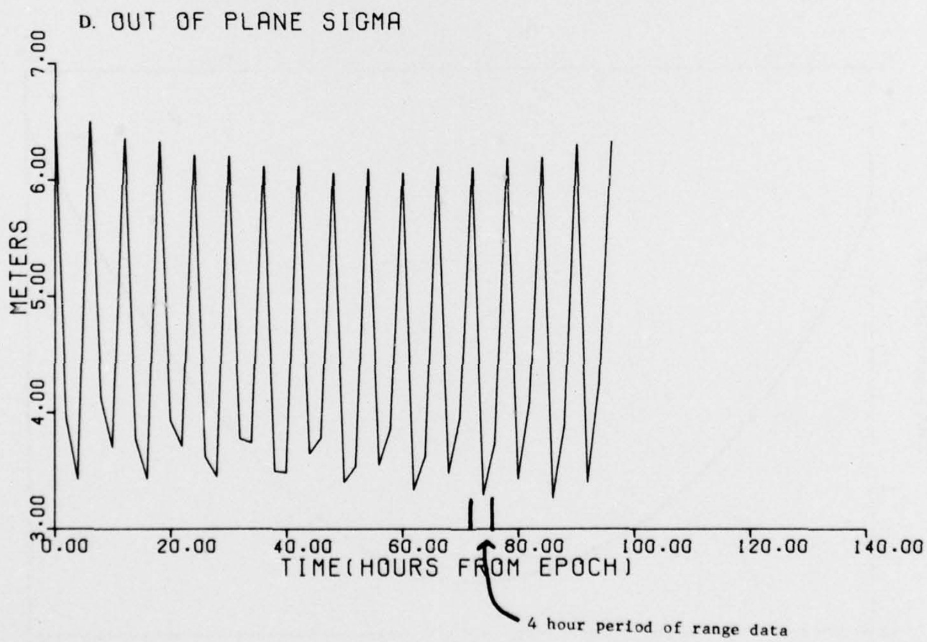


Figure 2. Standard Error in Satellite Position and Clock Bias from Range and Range Difference Data (Continued)

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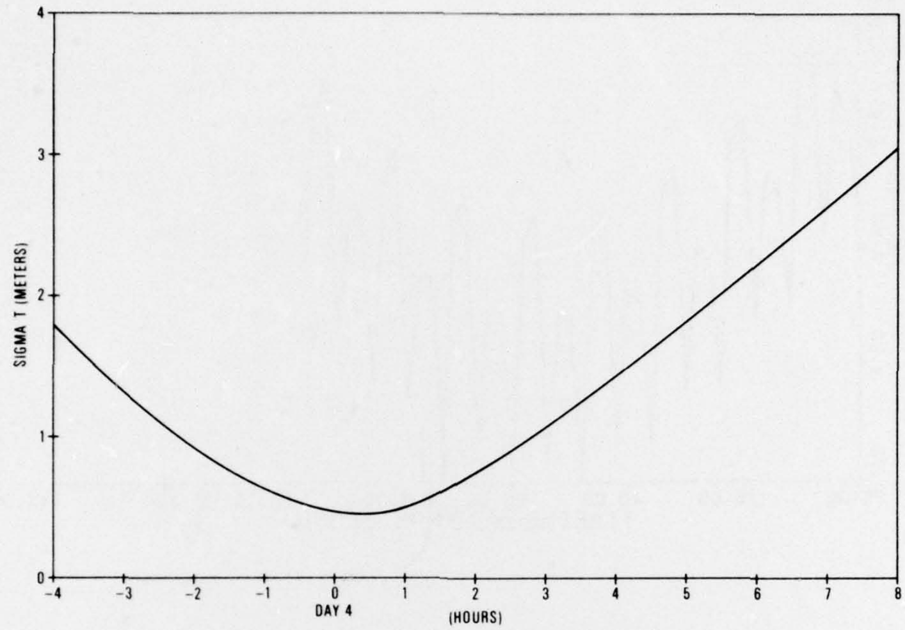

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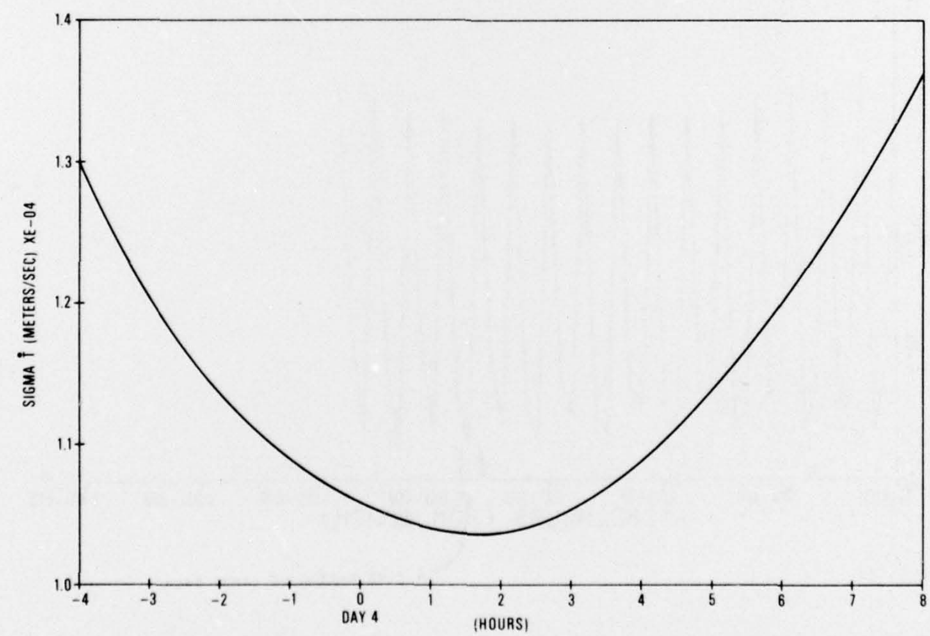

Figure 2. Standard Error in Satellite Position and Clock Bias from Range and Range Difference Data (Continued)

Table 1. Standard Error in Clock

	Bias	Rate	Aging
Station 1	3×10^4 ns	25920 ns/day	0 ns/day^2
Station 2	3×10^4 ns	25920 ns/day	0 ns/day^2
Station 3	3×10^4 ns	25920 ns/day	0 ns/day^2
Station 4	3×10^4 ns	25920 ns/day	0 ns/day^2
Station 5	0	0	0 ns/day^2
Satellite	3×10^4 ns	25920 ns/day	74.6496

Although there is some loss of statistical integrity in the use of the range observations in two forms, the loss is considered minor in view of other assumptions made.

The modified program, called EXPROG, is an extension of a computer program written for experimental purposes. Since it is not efficiently coded or suitable for maintenance as an operational program, it will be recoded properly to perform the same functions in the event that it is later decided to remain with the batch processor rather than to switch to a sequential processor.

RELATED DOCUMENTATION

In addition to logical and mathematical description of CELEST computer program,[4,5] draft copies of input guides and the programming of the program exist. An input guide will be written for the EXPROG computer program, but documentation will probably not be written since it is expected that the program will be recoded.

DESCRIPTION OF THE CELEST COMPUTER PROGRAM

CHARACTERISTICS OF THE PROGRAM

The CELEST computer program is designed to compute the orbit of a satellite from a variety of observations. General and detailed descriptions of the program are given by O'Toole in References 4 and 5. Therefore only a summary of applicable portions of the program will be given in this section. The CELEST program has

four characteristics listed below which are not found in most other orbit computation programs.

Propagation

Because the orbit solution is nonlinear, iterations are generally performed to obtain the final results. Since the computation of the satellite position is an expensive portion of the solution, CELEST obtains the final positions by propagation of the parameter corrections with the partial derivatives of position with respect to the parameters. Reintegration occurs only if the parameter corrections are outside the linear range, which occurs only for a small portion of the solutions made at NSWC/DL. The linear range is widened by minimizing approximations in the variational equations and partial derivation of the data function and by the use of orbital elements (nonsingular in eccentricity) as parameters rather than satellite position and velocity.

Pass Matrix Concept

In operations, reruns are frequently made to add data received late or to delete data points or passes which are erroneous; in simulations, reruns are frequently made with changes in station array, data span of the fit, parameters, or ***a-priori*** for parameters. In order to avoid recalculating the data function for all data points under the new conditions, CELEST forms and stores normal equations for subsets of the data. The partial normal equations are usually for data taken during one pass of the satellite over one station. The program can then be reentered using previously computed ephemerides and pass matrices to obtain a new solution by deletion of previous pass matrices, forming and adding new pass matrices, reducing the number of parameters, or changing the ***a-priori*** values of the parameters.

Convenient Data Filtering and Program Control

CELEST has extensive automatic filtering capability to detect bad data points or erroneous passes and to assign data weights. An interactive graphics capability exists to manually override the automatic tests, to extract diagnostic data, and to indicate reruns discussed under the Pass Matrix Concept.

Short Arc and Span Matrix Concepts

The short arc concept allows automatic subdivision of a long orbit fit into a series of successive overlapping orbit fits, with preselected lengths of overlap and automatic change of the preselected overlap if insufficient data are available using linear operations with the pass matrices, if desired. The span matrix concept is the reverse process where normal equations formed for successive spans can be combined even if different reference ephemerides were used in this formulation. The propagation and pass matrix concept should be especially useful in determining orbits optimized for SATRACK conditions. Thus, maximum use of computations already performed for the Joint Project Office in providing the MCS with reference ephemerides will be employed in the SATRACK project.

EQUATIONS OF MOTION

The CELEST program computes satellite positions by numerical integration of the equations of motion in an inertial reference frame defined by mean equator and equinox of an epoch usually selected to by 1950.0. The integration is by a Cowell method of order and interval which will be selected as the 10^{th} and 300 sec for GPS satellites. The variational equations for constants of integration, drag, and solar radiation are integrated by the same method. The earth's gravitational forces are rotated to the inertial frame using the hour angle of Greenwich defined by an extrapolation of Naval Observatory corrections for (UTC-UT1), and using precession and nutation values given in the American Ephemeris and Nautical Almanac.* An (8,8) truncation of the DoD WGS-72 gravity field is used in the computations for GPS satellites initially. The direct acceleration of the sun and moon is accounted for and the tidal forces of these bodies are represented using a value of 0.26 for Love's number and zero lag. (The value of 0.26 was obtained in a geodetic solution based on observation of low altitude satellites, and is believed to be low with respect to terrestrial values due to the neglected effects of ocean tides). Atmospheric density is represented by an attitude-dependent function, but drag will be set to zero for GPS satellites. For the Navigation Technology Satellite (NTS), the acceleration due to solar radiation depends on the orientation of the satellite and relative position of the satellite and sun as shown in Figure 3.[6] Earth and moon albedo effects will be neglected in initial computations. Relativistic effects are neglected in the equations of motion.

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*U. S. Government Printing Office, *American Ephemeris and Nautical Almanac*, Washington, DC, 1977.

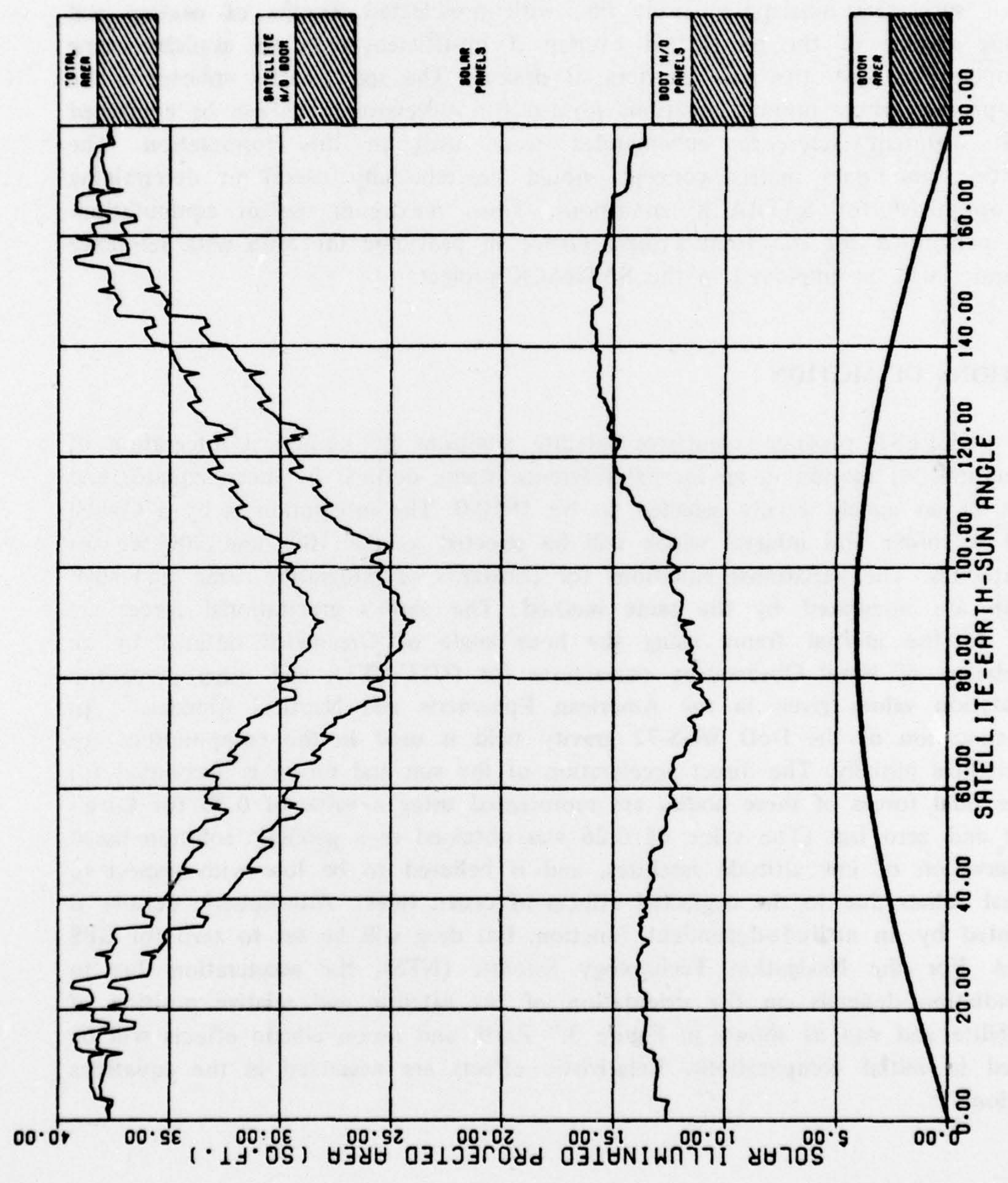

Figure 3. Satellite Illumination vs. Sun Angle

OBSERVATION EQUATION

For observation equations formed for GPS data, the field observations have been corrected in a preprocessing program for ionospheric delay, change in satellite and receiver station position during transit time of the signal, tropospheric delay, general and special relativistic effects, antenna offsets, and receiver delays. Therefore, computed range and range differences are vacuum values for satellite and receiver positions and the given observation times. Station position is rotated to the inertial frame through the same precession, nutation, and hour angle values described above for the gravity field after rotation from the instantaneous pole to the C10 pole through positions of the pole extrapolated from values computed by the Defense Mapping Agency Topographic Center on the basis of Doppler observation of Navy Navigation Satellites. Station positions are DoD WGS-72 values determined by transferring GEOCEIVER-derived locations from the NWL 9D system. Partial derivatives are formed for the six orbit constants, three scaling factors for solar radiation in a satellite-oriented reference frame, thrust parameters, three components of station position, tropospheric refraction scaling parameters, satellite frequency bias, and frequency drift. Normal equations for these parameters are written in a file for each pass of range difference data for each satellite over each station in a 7-day period. During periods of SATRACK operation, corresponding normal equations will be written for range data with the satellite frequency bias, and drift partials replaced by satellite clock bias, rate and aging partial derivatives for the corresponding station clock parameters). The normal equations are then augmented[5] to include two pair of gravity coefficients, if necessary. (If a momentum dump occurs during a pass, the entire pass will be considered to have occurred either prior to or after the dump according to whether time of closest approach is prior to or after the time of the dump.)

ORBIT SOLUTION FOR THE JOINT PROJECT OFFICE

For reference trajectories computed for the Joint Project Office, solutions will be based on range difference observations for each satellite in sequence. The normal equations for each satellite pass will be augmented with weights corresponding to 1 m in standard error for each component of station position (as a method of degrading data for errors in the mathematical model), and 5 percent in tropospheric refraction bias. Each equation will be reduced to eliminate explicit appearance[5] of station position, frequency bias, and refraction bias. The normal equations for each pass are then added and augmented with weights corresponding to 5 percent in each component of solar radiation reflectivity. The solution of the equations is then iterated, if necessary. For SATRACK operations, the steps in this section are ignored, and the normal equations for each pass as described in the previous section are input to the EXPROG program for solutions.

DESCRIPTION OF THE EXPROG COMPUTER PROGRAM

PURPOSE

The primary outputs of the CELEST computer runs used as input to the EXPROG program are the trajectory files and the pass matrix files. A numbered trajectory file for each satellite contains the positions of the satellite and the partial derivatives of position with respect to the dynamics parameters (orbit constants, drag, radiation parameters, gravity coefficients, and thrust parameters) used in forming the pass matrices. The pass matrix files have been satellite-ordered in one numbered file in a preliminary computer run so that a physical end-of-file mark appears between matrices for different satellites. A separate file is written for range and range difference data. The matrix for each pass of a satellite over a station includes as parameters the dynamic parameters, the three components of station position, refraction bias, and two or three satellite oscillator parameters (frequency and frequency drift for range difference data or time bias and rate and aging for range data). The purpose of the EXPROG program is to expand the pass matrices to include station oscillator parameters, add weights corresponding to ***a-priori*** assumptions concerning the parameters, add and solve the matrices, and adjust the reference trajectory for the parameter corrections obtained in the solution. The covariance of the solution at epoch is also propagated to times of interest. The SATRACK program logic is presented in Figure 4.

PASS MATRIX OPERATIONS

The order of the pass matrices is as follows:

1. Dynamic parameters
2. Station coordinates
3. Refraction scaling parameters
4. Satellite oscillator parameters

Only the upper triangular portion of the symmetric normal equation is on the input file. The EXPROG program will reform the pass matrix so that the satellite oscillator parameters appear after the dynamic parameters which are followed by the station oscillator parameters. Explicit appearance of the station position and

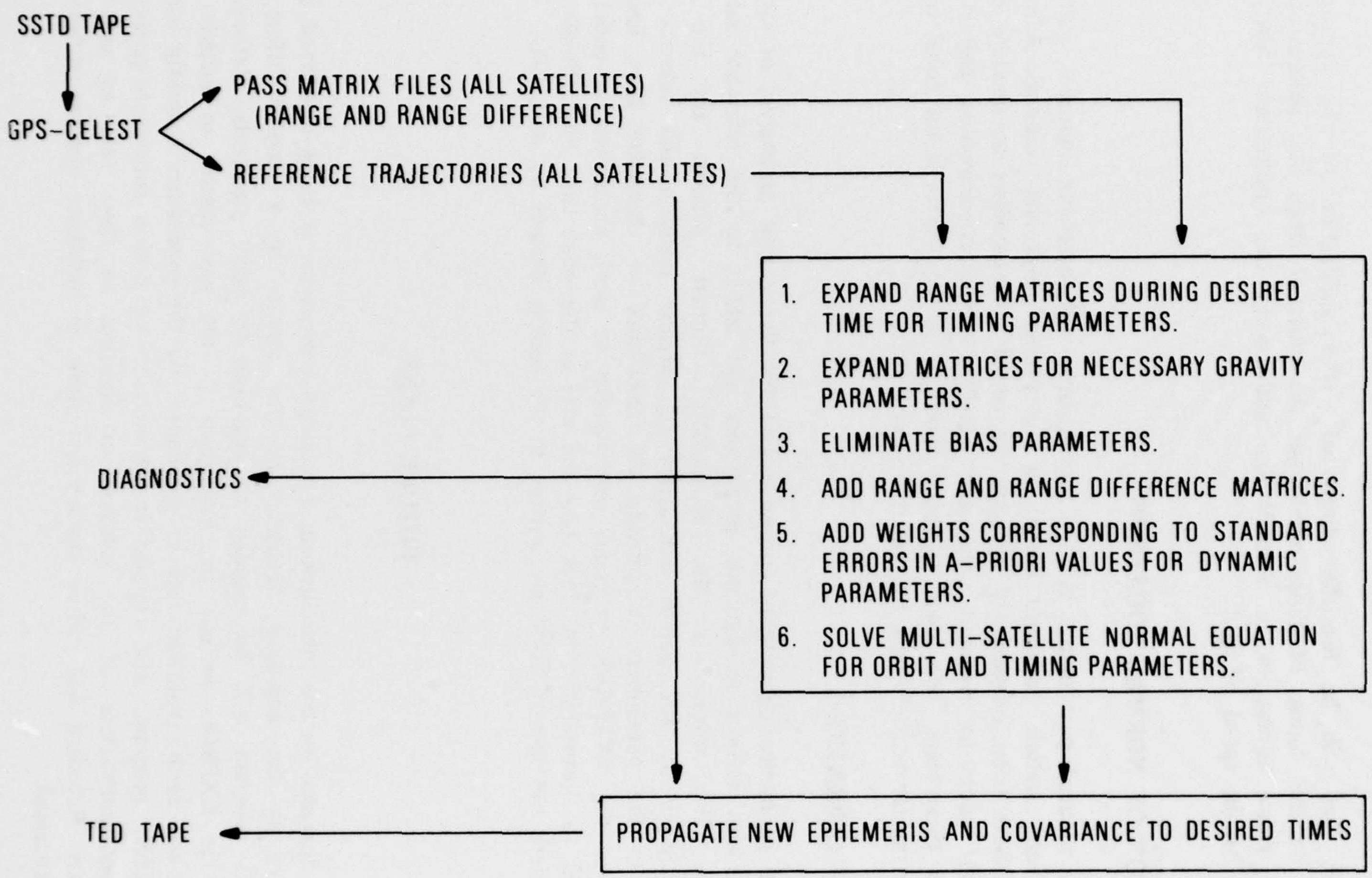

Figure 4. SATRACK Program Logic

refraction bias will be formally eliminated[7] after application of the appropriate weights. In the course of those operations, the units of clock bias parameters are changed from kilometers to seconds by multiplying the appropriate rows and columns by the speed of light.

SOLUTION OF NORMAL EQUATIONS

The reduced pass matrix is then accumulated with preceding matrices, with the satellite and station partitions stored in the proper rows and columns. After all matrices have been accumulated, weights are added corresponding to standard errors in ***a-priori*** values for dynamic parameters, satellite oscillator parameters, and station oscillator parameters. The lower triangular portion of the matrix is set equal to the upper triangular portion, and the equations are solved.

OUTPUT OPERATIONS

The parameter corrections are multiplied by the partial derivatives of satellite position with respect to dynamic parameters and added to the reference satellite positions. The inverse of the accumulated normal matrices are pre- and post-multiplied by the partial derivatives of satellite position and velocity with respect to the parameters to provide the covariance at successive time lines of interest in the SATRACK program. Uncertainties in clock parameters at epoch are converted to uncertainties in clock bias and rate at the same time lines. Finally, the output data and identification are written in the format desired by APL/JHU.

FUTURE PLANS

As discussed in the introduction, a sequential processor is being developed as an alternative to the approach described in this report. In a parallel effort, the EXPROG program will be recoded to conform to Navy standards. Refinements required in EXPROG include the expansion of the pass matrix to include pole position and earth's rotation rate as parameters by the procedures currently used in the CELEST program. Also planned is the inclusion of station coordinate parameters as proper parameters of the solution in addition to their role as pass bias parameters. Recoding will reduce storage and allow an indefinite number of satellites to be processed.

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